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THE PROBLEM OF INDUCED 'BLOCK MOTION' RELATED TO DEEP UNDERGROU--ETC(U)

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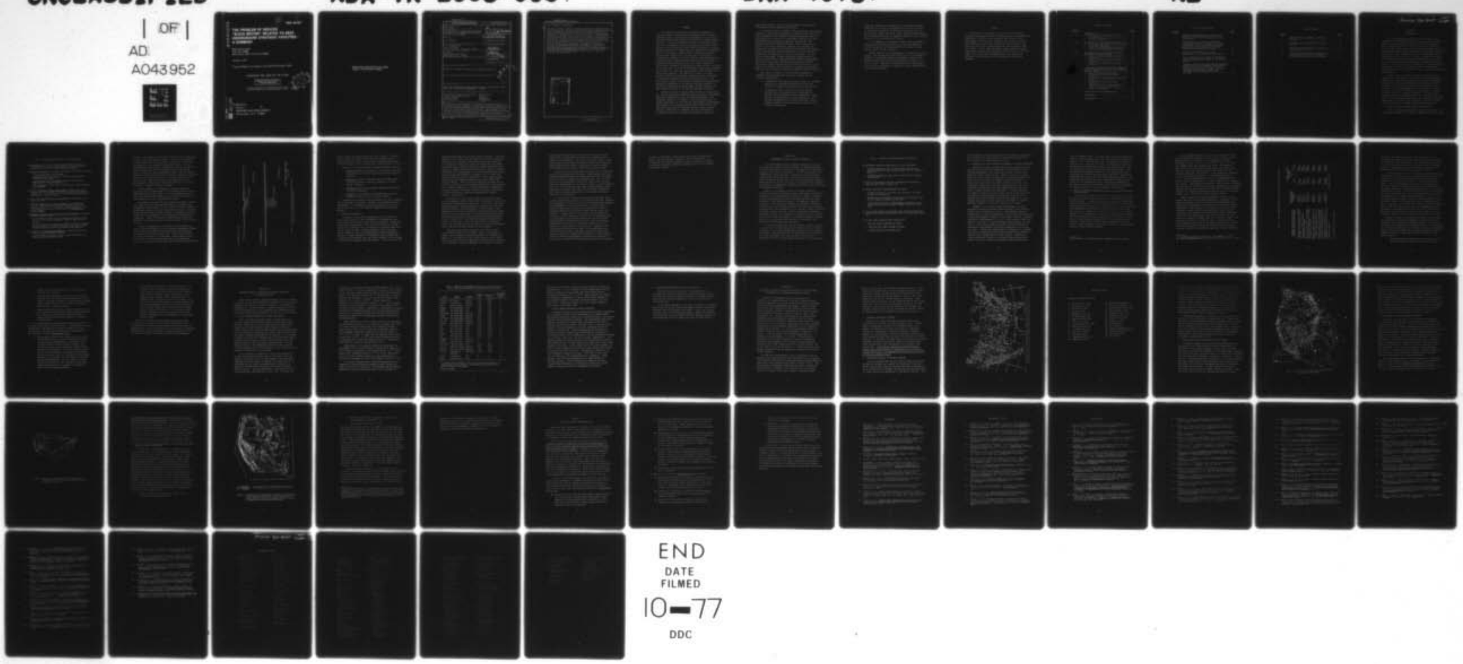

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THE PROBLEM OF INDUCED "BLOCK MOTION" RELATED TO DEEP UNDERGROUND STRATEGIC FACILITIES— A SUMMARY

R&D Associates
P.O. Box 9695
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January 1977

Topical Report for Period June 1975—October 1976

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The "block motion" problem of explosion-induced differential displacement along geologic discontinuities must be better understood to adequately design and site underground strategic facilities that would survive wartime threats. The purpose of this investigation is to review pertinent literature, develop concepts addressing current understanding of explosion-induced block motions, and identify research that could quantify risks for → next page

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20. ABSTRACT (Continued)

cont. particular sites. The block motion problem is concerned both with those motions driven or dominated by the explosion-induced stress transients and with those motions "triggered" by the explosions but dominated by the partial relief of pre-stress conditions. Emphasis is given to the problem of "triggered" motions because this is the aspect of greatest uncertainty and because the limited evidence is suggestive that differential slip can be triggered at considerable distance from the explosion, depending greatly upon in-situ stress conditions. Methods for avoiding, relieving, absorbing, and resisting explosion-induced block motions are addressed; and it is concluded that quantifying the block motion problem appears difficult but not hopeless. An adequate predictive capability does not exist and should be a primary goal of subsequent research and development.

SUMMARY

The threat of block motion, defined to encompass all explosion-induced differential displacement along geologic discontinuities, is an important consideration in siting and designing underground strategic facilities for maximum system survival. A predictive capability does not presently exist that can satisfactorily assure avoidance of the block motion problem by site selection, relief from the problem by in-situ stress alteration, or assure that the design of an underground facility can absorb a block motion of uncertain magnitude. The principal reason for this situation is that there is insufficient knowledge of in-situ stress field conditions and failure criteria associated with faults and other possible weakness discontinuities that are the likely locations of block motion responses to explosively induced stress transients. It is clear that the focus of developing a predictive capability should be to set lower and upper bounds on the credible block motion displacements. The motions of concern are those directly induced by explosions interacting with "imbalanced" or excessive prestress conditions within the earth. The block motion problem also includes differential displacements induced by explosions in the rupture and spall regions of surface and near-surface bursts where induced stresses overwhelm either balanced or imbalanced prestress conditions.

Emphasis in this review has been directed at identifying the risk of explosions triggering block motions in prestressed media and examining ways of minimizing the problem. The triggering problem is of special interest because there is greater uncertainty of the risk and more distant displacements are credible for a given explosion threat than would be the case for conditions where stored tectonic stress is small. The major deficiency in assessing the risk of explosion-triggered block motion is that the threats are surface or

near-surface bursts, and all known triggered block motions are associated with contained explosions.

It is this writer's judgment, after reviewing a significant sampling of the pertinent published literature, that the block motion problem can be resolved to within acceptable limits of uncertainty by a research and development program that integrates theoretical analysis, empirical observation, and laboratory and field experimentation. Such an approach to refine a predictive capability combined with the best of present day or advanced site selection and evaluation methods holds the potential of both identifying low risk sites and determining the magnitude of risk for such sites. If this can be accomplished, further assurances appear possible by designing structures to absorb maximum credible displacements that cannot be avoided; employing measures such as water injection to assist further relief of in-situ stress in local regions of greatest threat potential; and employing measures such as grout injection to locally strengthen zones of weakness.

The indirect evidence of block motions triggered by contained nuclear detonations primarily consists of the following observations:

1. Intermediate and high yield events result in increased seismicity or earthquake aftershocks within the vicinity of several kilometers from the explosions.
2. Differential slip at the ground surface across pre-existing faults occurs out to distances of several thousand meters from the explosions. These motions are consistently in the direction of past geologic movements for the faults affected, and the partial release of tectonic stress (or natural prestress) is indicated.

These data lead to the interpretation that where prestress conditions are similar to experience at several locations at the Nevada Test Site, the Central Nevada Test Site, or the Amchitka, Alaska Test Site, then triggered block motions can be expected to occur to distances where explosion-induced strains are of the order of 10^{-6} cm/cm.

It is necessary to understand these effects produced by contained nuclear detonations so that the real threat of distant triggering of block motions from surface or near-surface bursts can be evaluated.

Recent advances in tectonophysics, seismology, structural geology, and rock mechanics have resulted in an increased emphasis in geodynamic studies and especially efforts to better establish the nature and magnitude of stress in the earth's crust. Important contributions to the development of a block motion predictive capability can be expected from these combined efforts.

PREFACE

Since much of this report is the result of reviewing published literature and many contributions are not specifically referenced, I would like to recognize the authors in the bibliography for their many contributions. Critical review, encouragement, and fruitful discussions contributing to this study have been made by Hank Cooper and Dave Srinivasa (RDA); Dave Oakley, Lt.Col. Danny Burgess, Joseph Lacomb and Eugene Sevin (DNA); Howard Pratt (Terratek); Scott Blouin, (U.S. Army CRREL); Jimmie Bratton (AF Weapons Lab); and various U.S. Geological Survey personnel in coordination with William Twenhofel.

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SECTION I

INTRODUCTION

If an underground communication facility were to be constructed, it should be located at a reasonably accessible depth, presumably less than 2.5 km, and still be able to survive and accomplish its mission under threat conditions of very large yield surface or near-surface nuclear explosions. The site should be located in rock that has suitable electrical properties so that communication could be performed without transmission cable continuity. Certain concepts of strategic underground facilities are extensive, where the areal extent of a site may be tens or even hundreds of square kilometers. Further, it would be ideal to locate such an underground structure below materials that absorb or reflect the explosion-induced stress so as to minimize damage to subsurface structures and personnel.

The block motion problem refers to explosion-induced differential displacement along geologic discontinuities and emerges when stress fields from very large yield explosions interact with such inhomogeneities and threaten to damage subsurface structures. The purpose of this review is to provide an initial assessment of the block motion problem to assist the focus of research and development. Hopefully this will lead to an improved capability for predicting explosion-induced displacements and for limiting their magnitude. If this can be accomplished, then efforts in strategic system design and siting can proceed in a manner in which risks and costs can be better evaluated and minimized.

1. THE BLOCK MOTION PROBLEM (TERMS AND CONCEPTS)

Table 1 defines some important terms and outlines a few concepts found useful in helping to perceive the block motion

Table 1. The Block Motion Problem - Terms and Concepts

- Block Motion – Refers to explosion-induced differential motion or displacement across faults, joints, bedding or other geostructural discontinuities occurring in underground rock formations.

- Regional Conditions which interact and determine block motion occurrences:
  - In-situ or prestress field variations
  - Induced stress field variations in space and time produced by explosion or other means
  - Failure criteria field variations of both the various earth materials and included discontinuities
  - Fault parameters: length, depth, dip orientation, motion magnitude and direction.

- Relatively balanced regional stress fields are areas where stress gradients are minimal; where vertical stress variations are primarily gravitational - ρgh; and where horizontal stresses are approximately hydrostatic to lithostatic loads.

- Relatively imbalanced regional stress fields are regions with large stress gradients.

- Relatively balanced local stress components are those where the principal stress axes are nearly equal in magnitude and typically approximate local ρgh values and nearly isotropic conditions. Significant departures would be termed relatively imbalanced local stress components.

- Regions of active or accumulating in-situ stress anomalies – Responding to dynamic tectonic forces.
  - To be avoided in siting as natural processes occasionally exceed failure criteria causing earthquakes, aseismic creep, and fault motions.
  - Few regions are totally isolated or buffered from tectonic processes; however, extremely slow stress accumulation may present virtually the same problem as presented with residual stress anomalies.

- "Locked-in" or residual stress anomalies in regions reflecting past or slowly accumulating tectonic activity.
  - To be minimized or avoided in siting to reduce block motion risk from explosion-induced stress relief.

problem. The concept of relatively balanced versus imbalanced in-situ stress introduced in Table 1 refers to stress field conditions thought to be especially important in determining susceptibility to explosion-induced block motion. It is hypothesized on the basis of earthquake activity records and in-situ stress data that differences exist in the stress state of rock over large geographical areas, such as physiographic provinces within the United States, individual mountain ranges or even from mile to mile. Such an hypothesis fits the facts and leads to the conjecture supported by a few experiments or observations that external forces can trigger the partial release of built-in stress.

Such an effect, if triggered by nuclear explosions might have major consequences for war fighting systems unless considered during their design. It is the purpose of this paper to explore these concepts and to identify research that could quantify the risk for particular sites.

The concept of block motion triggering relates to events that alter the in-situ stress condition to the extent that differential slip occurs. In this report the term "triggering" specifically refers to block motions which reflect a response to explosion-induced stresses coupled to prestress conditions rather than only responding to the explosion-induced stress transients. Where the explosion-induced stress conditions dominate the rock mass failure the term "driven" block motions is used.

Figure 1 schematically illustrates in cross-sectional view the gross differences in block motion development between large yield near-surface nuclear explosions and contained or deeply buried nuclear explosions. Driven block motions are generally thought to be confined to the rupture region surrounding the detonation and the spall and rarefaction region at the earth's free-surface where stress wave reflections

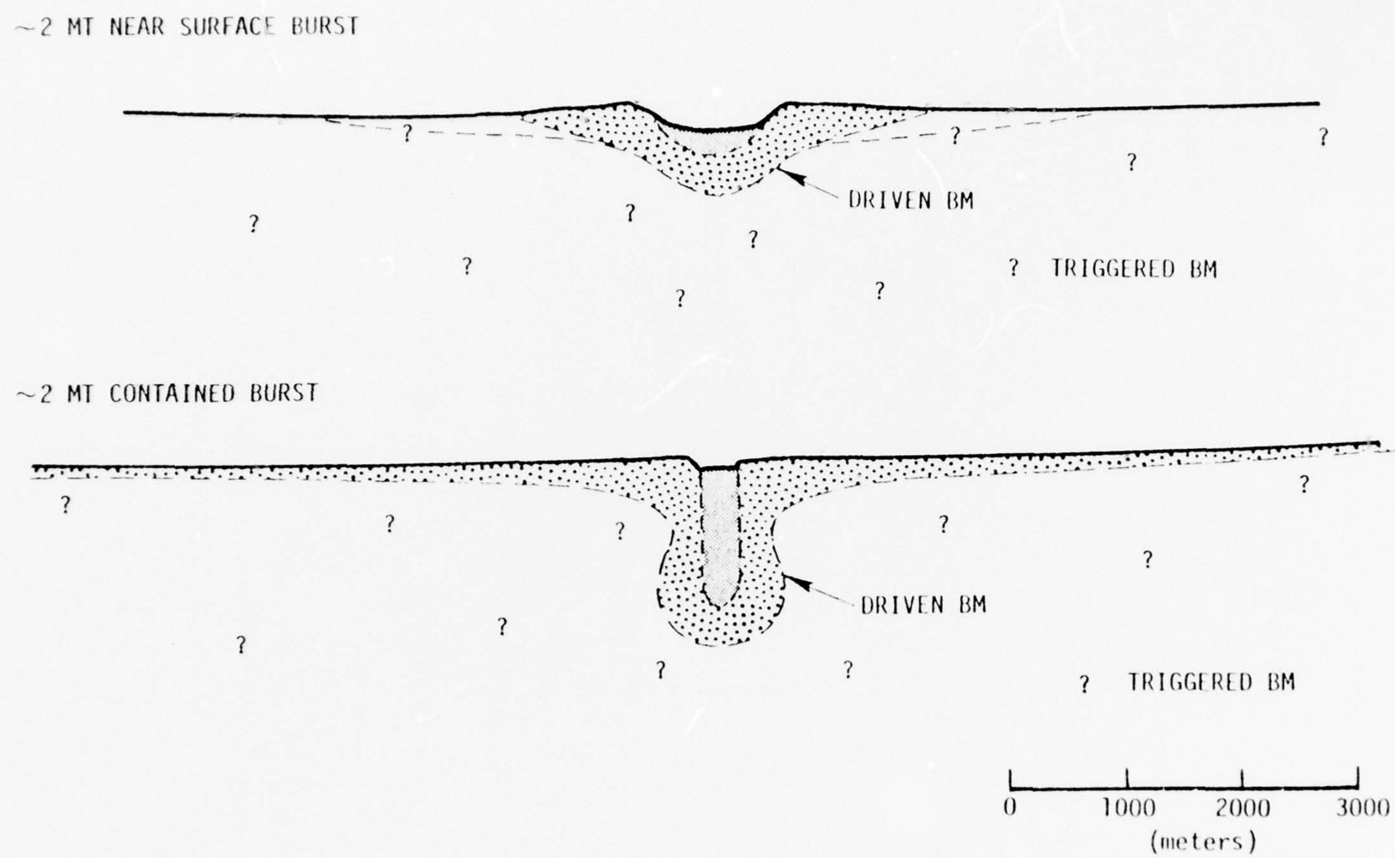

Figure 1. Schematic Cross-Section of Large Yield Nuclear Bursts Showing Block Motion (BM) Distribution

occur, putting the near-surface rock into tension. Although the magnitude and limits of driven block motions are not highly predictable, much more is known of these effects than triggered block motions (labeled with a question mark in Figure 1).

Solution of the block motion triggering problem involves:

1. Avoiding severely imbalanced in-situ stress conditions using advanced site evaluation and selection methodologies.

2. Relieving severely imbalanced in-situ stress conditions using water injection, explosion, or other suitable methods.

3. Absorbing block motions without system failure using creative engineering.

4. Resisting block motions by strengthening the weaknesses and changing local failure criteria.

Depending upon specific site conditions, all four approaches may be required for success. Further, all approaches require development of a reasonable predictive capability, and that must be the goal of a block motion research and development program.

2. OVERVIEW PERSPECTIVE

The earth's curst and lithosphere are on the order of 20 to 150 km thick for the continental land masses and are less dense and much more rigid than the underlying (supporting) mantle and asthenosphere. Thus, the land masses in a sense float upon a substrate that is thought to be slowly mobile due to the action of heat, viscous convective flow, and other poorly understood driving forces behind crustal deformation. Regions of broad upwarping or downwarping may be responding to isostatic adjustment with the crustal element in the process of approaching gravitational equilibrium. It is now clear that

crustal plates have been and are slowly "drifting." The more obvious driving forces are associated with regions receiving injections of rock magma, thus adding new crustal material to the plates. These major zones are associated with nearly continuous global oceanic ridges that divide the earth into some six or seven principal crustal plates, which in turn are subdivided into approximately 30 distinguishable major plates. With more precise geodynamic information it is likely that numerous subplates will be identified. These overall plate interactions are commonly referred to as the "Rigid Plate Tectonic Theory." With this very simplified picture, we can see that the fragile crust is being subjected to gravitational pull, lateral forces due to plate interactions, buoyant and upwelling forces from below, as well as changing load conditions associated with erosional processes and climatic (glacial) conditions.

The earth is a few billion years old, and most rocks within accessible depth of the earth's crust are a few million to several hundred million years old. The earth's crust has been subjected to numerous periods of deformation that have produced abundant failure surfaces in most regions. Rock permeability to water is typically increased with such deformation of brittle materials, so it can be expected that most pore spaces associated with deformation-produced structures (faults, joints, etc.) are water-saturated at depths below about 300 m or less. Fluid or pore pressure conditions within such discontinuities are likely to have a considerable effect upon the failure criteria of such features.

Because we know much more about the surficial earth crust features than we do at depth, there is a tendency to expect such features as fracture frequency to decrease with depth. On the contrary, older rocks generally occur below the younger ones and have experienced more periods of deformation; therefore, fracture frequency will generally increase

with depth for materials in which brittle failure occurs. Observations of deep mines in Africa and elsewhere tend to support this generality. In trying to quantify this, it has been found that vertical drill holes provide a poor sampling method because near-vertical fracturing in many regions is more common than low angle or flat-lying failure planes.

Caution should be exercised with regard to our preconceptions of in-situ stress with depth. Some materials such as unconsolidated water-saturated sediments and salt can support only low levels of stress and readily creep. This is also true of the asthenosphere and certain deep crustal regions where the temperatures are in excess of 600° C. With competent rock of a brittle failure type, the in-situ stress is often observed to be quite high, even at the surface, indicating that lateral stress components are not readily relieved at the earth's free surface.

It is certainly important to obtain a great deal more in-situ stress data since so little presently exists. Because of the expense of obtaining the data and because each measurement represents a very limited sample, investigations of indirect geophysical and geologic indicators of in-situ stress anomalies and conditions should also be given high priority. Coupled with in-situ stress investigations is the very difficult problem of making in-situ determinations of the properties of discontinuities such as faults that determine local conditions for failure (failure criteria). Measurement of the in-situ frictional coefficients of a fracture or fault zone is very difficult. Laboratory and field experimentation may be able to set reasonable limit values which can guide frictional coefficient values that could be assumed in computational modeling of block motions. Relating observed displacement variations along faults to frictional variations along those same faults may be possible

in some circumstances. This type of empirical evidence would help in failure criteria estimation and in determining if it is feasible to construct patches of high friction along faults in regions surrounding underground workings to limit or prevent local block motions.

SECTION II

EARTHQUAKE AND BLOCK MOTION TRIGGERING

In regions where in-situ stresses accumulate with time as a result of dynamic earth processes, it seems reasonable to expect precursory or premonitory phenomena to be detectable prior to some natural earthquakes. If a siting program that successfully avoids regions of significant in-situ stress accumulation can be achieved, studies revealing more definitive information about natural and induced earthquake triggering mechanisms would be more relevant to the block motion problem than studies of premonitory phenomena currently being emphasized in earthquake research.

Table 2 is a summary listing of various classes of evidence indicating triggered natural earthquakes, man-induced earthquakes, and triggered block motions. There is evidence of large earthquakes triggering smaller ones and also some evidence of the reverse situation. Propagation rates from one event to the other that provide the clearest evidence of triggering are approximately equal to the shear wave velocity characteristic of the specific local regions. Spatial relations of seismic events with time (usually much slower indicated propagation rates) are suggestive of triggering that resulted from in-situ stress adjustment to preceding events or possibly from failure criteria alteration due to increased fluid pressure or other hydrologic responses.

In certain regions such as the Brawley, California area (a portion of the San Andreas fault system), there is evidence of correlation of small earthquakes with gravity tide maxima and minima. Such examples help to demonstrate that triggering is a real phenomenon, but adds little to the problem of assessing the risk of block motion triggering in more aseismic

Table 2. Evidence for Triggering Earth Strain Release

- Earthquakes sometimes trigger smaller or larger earthquakes

  - Triggering propagation rate is about equal to the shear wave velocity generated by the earthquake thought to be the triggering agent [1].

  - Triggering propagated by quasi-static strain and fluid pressure redistribution.

- Gravity tide triggering some small earthquakes--"the straw that broke the camel's back" situation [2].

- Nuclear explosions (intermediate and high yield)

  - Increase seismicity for a few hours to a few days in the range of several kilometers [3].

  - Observed fault displacements (at the surface) to distances of one to six kilometers (depending on yield) [4].

  - Limited observed subsurface displacements to distances of less than a few hundred meters (HARDHAT, GUMDROP, MIGHTY EPIC events) [5,6].

- In-situ stress release by explosions occurs within the direct range of fracturing where no distant block motion is observed (BILBY event) [7].

- In-situ stress release by water injection [8].

  - Rocky Mt. Arsenal experience near Denver.

  - USGS controlled study at Rangely, Colorado.

  - Increase seismicity at some dam sites.

regions where in-situ stresses may be significantly imbalanced but "locked-in" so that there is little stress change over time unless it is induced by acts of man.

1. EARTHQUAKE AND FAULT MOTIONS TRIGGERED BY NUCLEAR EXPLOSIONS

Earthquake triggering from underground contained nuclear explosions has been most documented at the Nevada Test Site and the supplemental test sites near Tonopah, Nevada, and Amchitka Island, Alaska [9,10]. There is little or no documentation for surface, near-surface, or cratering explosions. Where contained explosions appear to cause increases in seismicity, the region is already seismically active. For contained nuclear explosions with yields greater than 500 kT, increases in seismicity are often observable for periods of days to weeks following the detonation. In most cases the "triggered" events are located within 20 km of the detonation, but some have been reported at distances as far as 40 km. Surface fault displacements have not been observed at these extreme distances, and the nature of the events in terms of physical changes in the source regions is not known.

Movement, or at least surface displacement, on some pre-existing faults has been observed within a few thousand meters from the explosion [11,12]. The permanent relative displacement on faults consistently occurs in the same direction as past displacements resulting from natural tectonic processes. Horizontal displacements of 0.1 to 1 m and vertical displacements as large as 4.5 m have occurred along portions of a few faults. The in-situ stress conditions and the magnitide of subsurface displacements along such pre-existing faults are not known. Underground observations of anomalous or triggered block motions resulting from nuclear explosions are few and generally the documentation is very limited. Anomalously large motions are thought to have been observed beyond the general limits of fracturing induced by the explosions for

the 5-kT HARDHAT event.* In this case, the block motion with possible lateral displacement of a few meters was confined to within a 5- to 8-m-wide fault zone intersecting the emplacement drift at a distance of 143 m. The effective limits of fracturing and obvious block motion are less than 130 m from the detonation except for the above-mentioned anomaly. The orientation and apparent motion of this fracture zone are consistent with the strike-slip motion and N60°E orientation determined by analysis of the seismic radiation pattern. The observed block motion has been intrepreted by some as local caving of the prefractured rock. Additional documentation by careful excavation for pre-shot drift offsets is necessary to determine the nature of the apparent block motion.

2. ORDER OF MAGNITUDE EMPIRICAL SCALING OF EXPLOSION-INDUCED BLOCK MOTIONS

A definitive review of block motion responses to nuclear explosion events is needed and was not accomplished as a part of this review. A brief examination of some of the experience enables estimates of order of magnitude effects to be made for block motions as a function of explosion yield; such observations are associated with contained nuclear explosions where cube root scaling of distances are assumed to apply to the observed effects. It is important to keep in mind that these estimates are not predictions but serve primarily to illustrate a difference in block motions that appear to involve triggering and release of some stored tectonic energy compared with block motions caused primarily from direct explosion-induced stresses exceeding local failure criteria.

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*Observations not documented but remembered by this author.

In an assumed balanced in-situ stress condition, block motions induced by explosions in hard rock diminish to small displacements of less than a few centimeters at scaled distances of about 75 $W^{1/3}$ (m) or 245 $W^{1/3}$ (ft).* For the 5-kT HARDHAT test this distance was 128 m, the distance where peak free field radial stress dropped to about 1 kbar and where open drift damage became minor (except for the anomalous possible displacement of a few meters at a distance of 143 m mentioned previously). The scaled distance of 75 $W^{1/3}$ (m) may approximate that limit of appreciable block motion where the triggering of in-situ stress is not a significant factor. This generality certainly needs further refinement and verification for contained nuclear explosions and is probably conservative or over-predicts significantly for surface, near-surface, and cratering explosions where the source is not well coupled into a hard and fractured response medium.

Table 3 compares the above-estimated "limit" of block motion response to contained explosions in "balanced" in-situ stress conditions with other block motion experience where triggering and presumably "imbalanced" in-situ stress conditions exist. The indication from Table 3 is that if normal "balanced" in-situ stress conditions exist at a site and triggered block motions are successfully avoided, then there would not be an appreciable block motion problem for deep subsurface ranges of greater than 750 m (2460 ft) from a 1-MT explosion, or 3470 m (11,380 ft) from a 100-MT explosion. These estimates of ranges to the effective limits of induced block motions refer to distances below near-surface bursts that are coupled to the hard rock as well as if the explosion

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*W is explosive yield in kilotons. For example, 75 $W^{1/3}$ for the 5-kT HARDHAT event is 75 x $(5)^{1/3}$ = 7.5 x 1.71 = 128 m.

Table 3. Order of Magnitude Empirical Scaling of Block Motions at NTS

DISTANCE FROM SHOT POINT TO THE EFFECTIVE LIMIT OF BLOCK MOTION	SCALING FORMULA[a] (APPROXIMATE) (m/ft)	ESTIMATED DISTANCE FROM THREAT (m/ft)	
		1 MT	100 MT
"Balanced" in-situ stress; contained detonation in fractured hard rock	$75\ W^{1/3}$ ($245\ W^{1/3}$)	750 (2,460)	3,470 (11,380)
Inferred subsurface "triggered" block motion at HARDHAT	$84\ W^{1/3}$ ($276\ W^{1/3}$)	840 (2,760)	3,890 (12,760)
Observed surface fault displacement limit for the Yucca Fault "triggered" by contained explosions	$300\ W^{1/3}$ ($1,000\ W^{1/3}$)	3,060 (10,000)	14,000 (46,000)
Observed surface fault displacement limit for the area #3 fault "triggered" by contained explosions	$150\ W^{1/3}$ ($500\ W^{1/3}$)	1,500 (5,000)	7,000 (23,000)
Observed surface fault displacement limit for Pahute Mesa major faults "triggered" by contained explosions	$600\ W^{1/3}$ ($2,000\ W^{1/3}$)	6,000 (20,000)	28,000 (93,000)
Triggered seismic events but no knowledge of associated block motions	$2,000\ W^{1/3}$ ($6,600\ W^{1/3}$)	20,000 (66,000)	93,000 (305,000)
Cratering explosions	-- Virtually no data --		

[a] W = Explosive yield in kilotons.

had been fully contained. With sites where much of the overburden absorbed or reflected the explosion-induced shock, less distance would be expected. The corresponding statement of effect with depth needs study to evaluate the additional feature of added hydrostatic or lithostatic stress and any differences in the rock failure criterion at depth.

It thus appears feasible to consider underground facility construction if anomalous or triggered block motions can be avoided and sites can be found which would minimize deep coupling of a significant fraction of the induced seismic energy. Facility components would still be vulnerable to the direct explosion effects and would require redundancy or extreme hardening to provide system integrity. The limited indications of Table 3 concerning triggering of block motions show that reasonable depths for facility construction cannot be considered safe without further research. Even if the explosion-induced stresses that may trigger subsurface block motions in regions of "imbalanced" in-situ stress scale as low as 1 percent (1-MT surface burst equal to 100-MT contained burst), the indicated lateral range to a probable limit of appreciable triggered block motions is 6 km to possibly as much as 20 km, and vertical ranges on the order of 5 km for conditions similar to those indicated at Pahute Mesa at NTS.

Because virtually all explosion-triggered block motions or indications of possible triggering are associated with contained explosions and the probable threats to underground facilities are surface or near-surface bursts, it is important to evaluate the differences in possible triggering mechanisms. There are distinct differences in explosion energy coupling between contained nuclear explosions and surface or near-surface bursts:

1. The peak stress and the width of the stress pulse of the dynamic shock loading is much less for near

surface (cratering) explosions at a given yield, material, and distance.

2. The explosion-produced cavity and its associated pressure and quasi-static stress history is of long duration--minutes to hours--for large yield contained bursts, where there is only a brief confinement in near-surface (cratering) bursts.

3. Block motions near the free surface associated with spall and shock reflections would be quite different for surface and near-surface bursts compared to deeply contained detonations because of geometric considerations.

By understanding the differences between contained and surface or near-surface bursts better, it is possible to place the apparent data supporting distant triggering of block motions from contained nuclear explosions in perspective. For instance it can be hypothesized that:

1. The triggered fault motions observed at the ground surface that follow the same displacement pattern as past natural displacements on the same faults (induced tectonic energy release evidence) are actually the spall and rarefaction induced release of near-surface strains. The strain release giving rise to the differential slip across pre-existing faults may be the result of released "drag stresses" adjacent to the faults that are residual from past natural displacements. If this model is correct, the block motions would be confined to relatively shallow depths and not to depths of thousands of meters as is generally surmised.

2. The observed aftershocks or induced seismicity (at ranges of out to several kilometers and depths to 5 km) resulting from large-yield contained nuclear explosions are induced strain responses to cavity expansion and collapse rather than responses to dynamic shock or pressure wave stress pulses. For surface or near-surface bursts the displacements due to "cavity pressure history" are less at depth and large lateral ranges than contained bursts because there is continual venting of rock and water vapor to the atmosphere as well as cavity growth being readily accommodated by displacements to the nearby ground surface.

Without a research and development program to define and solve the triggered block motion problem better, one would have to conclude from the present information that the problem poses a high risk because of our inability to adequately characterize a site and because a predictive capability has not been developed to enable satisfactory risk assessment.

SECTION III

POSSIBLE METHODS OF REDUCING POTENTIAL TRIGGERING OF BLOCK MOTIONS

Where stored tectonic stress anomalies cannot be avoided in siting, it may prove feasible to partially relieve excessive in-situ stress by water injection methods or by detonating explosions in critical regions. Another possibility that has not yet been explored is to strengthen the weakness discontinuities rather than attempting to reduce the in-situ stress.

1. IN-SITU STRESS RELIEVED BY NUCLEAR EXPLOSIONS

One of the most important areas of investigation of tectonic energy release from explosions comes from detailed analysis of Rayleigh- and Love-type seismic surface waves. These analyses are especially useful when the explosion source area is well characterized and when strain measurements are also obtained and coupled with other fault motion studies. With these combined measurements and analysis, it is possible to model and refine the interactions of the explosion-induced dynamic and quasi-static strain interactions with the pre-stress condition and to estimate the magnitude of in-situ tectonic stress. Comprehensive analysis of this type has not been systematically accomplished with very many explosion events, so much is yet to be learned.

It is generally accepted that Love waves generated at or near the explosion source have an association with the release of tectonic strain energy induced by the explosion. Observed Love wave energy is commonly much more than can be explained by near source inhomogeneities, indicating an important contribution coming from the release of stored tectonic strain. Various investigators have made use of the Love-to-Rayleigh wave amplitude ratio (L/R) to compute the

strength of the tectonic energy release component (F) of the double couple or Love wave component relative to that fraction of the explosion energy being carried by the surface Rayleigh waves. The relation of the ratio of the tectonic and explosion energy fractions (E_t/E_e) to the relative double couple strength (F) is $E_t/E_e \propto 4/3(F^2)$. These values for a number of events are listed in Table 4 [13]. Also, computed estimates of the magnitude of prestress have been made for a couple of these events. Experiments, measurements, analyses, and observed documentation have not often been sufficiently complete or coordinated between contributing disciplines to establish a definitive correspondence between calculations and observations.

When considering in-situ stress relief by the explosions or earthquake triggering, it is helpful to examine the range of strain conditions associated with observable effects. Tidal forces, which are not generally considered important to earthquake triggering, induce strains on the order of 10^{-8} to 10^{-10} cm/cm. It might then be expected that strains of the order of 10^{-4} to 10^{-7} cm/cm would be associated with triggering block motions and seismic events, or conversely, cause partial release of stored strain [14].

Observations of increased seismicity associated with the BENHAM event at NTS occurred to distances of about 15 km. This distance corresponds to an induced strain of 10^{-6} estimated from a measured strain of 10^{-7} at 30 km. The strain history at that distance seems to be best explained as a quasi-static response to the cavity pressure history [14,15].

It is thus indicated that contained explosions can be expected to relieve tectonic prestress almost completely within the region of the cavity and induced-fracture regions. Beyond that, partial prestress relief can be expected to

Table 4. Tectonic Strain-Release Characteristics from Underground Nuclear Explosions (Obtained from Surface Wave Analyses) [13]

Event	Region	Medium	D.C.* Strength (F)	Energy Ratio (E_t/E_e)	Estimated Pre-Stress (bars)
Piledriver	NTS Area 15	Granite	3.20	13.65	--
Hardhat	NTS Area 15	Granite	3.00	12.00	--
Shoal	Fallon, Nevada	Granite	0.90	1.05	--
Greeley	NTS Pahute Mesa	Tuff	1.60	3.41	--
Benham	NTS Pahute Mesa	Tuff	0.85	0.95	60
Chartreuse	NTS Pahute Mesa	Rhyolite	0.90	1.05	--
Duryea	NTS Pahute Mesa	Rhyolite	0.75	0.75	--
Half Beak	NTS Pahute Mesa	Rhyolite	0.67	0.60	--
Box Car	NTS Pahute Mesa	Rhyolite	0.59	0.46	--
Corduroy	NTS Yucca Flat	Quartzite	0.72	0.69	--
Cup	NTS Yucca Flat	Tuff	0.55	0.40	--
Bilby	NTS Yucca Flat	Tuff	0.47	0.29	75
Tan	NTS Yucca Flat	Tuff	0.39	0.20	--
Bronze	NTS Yucca Flat	Tuff	0.33	0.15	--
Buff	NTS Yucca Flat	Tuff	0.31	0.13	--
Haymaker	NTS Yucca Flat	Alluvium	0	0	--
Sedan**	NTS Yucca Flat	Alluvium	0	0	--
Faultless	Central, Nevada	Tuff	0.50	0.33	--
Milron	Amchitka, Alaska	Andesite	0.60	0.48	--
Cannikan	Amchitka, Alaska	Andesite	0.60	0.48	--
Rulison	Grand Valley, Colorado	SS.8 Shale	0.60	0.48	--
Salmon	Hattiesburg	Salt	0	0	--
Gnome	Carlsbad, N.M.	Salt	0	0	--

*F or double couple strength is the ratio of excitation strength of the double couple to the strength of the compressional component of the explosion-induced surface waves.

**Cratering event.

decrease as a function of distance with decreasing explosion-induced strain. It is unlikely that any appreciable tectonic strain release will occur where the induced quasi-static strains are less than 10^{-7} or 10^{-8}. More needs to be learned and analyzed to determine if stress relief using explosions is a practical means of reducing the block motion risk at a given site. These same studies will help better determine block motion triggering risks.

2. IN-SITU STRESS RELIEVED BY WATER INJECTION

Increased seismic activity associated with water or possibly the injection of other fluids sometimes occurs beneath dams, during hydrofracturing operations, hydraulic mining, liquid waste disposal and ground water recharge. The earthquakes that were observed coincide with waste water injections at the Rocky Mountain Arsenal near Denver, Colorado, led to more controlled studies of this phenomenon by the U.S. Geological Survey at Rangely, Colorado [8]. Here the magnitude and direction of in-situ principal stresses were determined by the hydraulic fracturing process to be compressive, with the principal stresses (S_1,S_2 and S_3) being 590, 430 and 315 bars, respectively. Resolving these onto the pre-existing fault plane where injection tests were run gave a shear stress of 80 bars and a total normal stress of 350 bars. It was found that a fluid pore pressure of about 275 bars reduced the effective normal stress sufficiently to induce slip along the fault. Earthquakes ceased when the fluid pressure dropped to 35 bars. More work of this type will contribute to the understanding of triggering, stress release, and the field determination of some aspects of failure criteria. Further research is needed to evaluate the practical feasibility of sufficiently relieving in-situ stress to reduce the risk of triggered block motion.

3. BLOCK MOTION REDUCTION BY GROUT INJECTION

Observed spatial variation of displacements along the same fault and rock deformation experimentation indicate that slip on faults is greatly restricted or ceases to propagate when high friction regions of the fault surface are encountered [16].

It may prove feasible to use water injection to accomplish some relief of in-situ stress and reduce friction along fault surfaces; then by switching from water to grout the regions penetrated may be strengthened markedly. Recent developments of high bonding strength grouts make this approach attractive for engineering study to reduce the risk of block motions.

SECTION IV

A REGIONAL APPROACH FOR AVOIDING AREAS OF IN-SITU STRESS ACCUMULATION AND IMBALANCED RESIDUAL STRESS

Seismic or earthquake zones are regions of the earth's crust characterized by relatively frequent stress release responding to in-situ stress accumulation associated with present-day deformational processes. Typically there are only partial relations of the patterns of the seismic zones to specific geologic features such as mountain ranges, the boundaries of basins, regions of uplift, major fault structures, etc. Seismic belts commonly cut across these structural and physiographic features as well as being aligned with them. Historic seismicity data record the surface location of earthquakes (epicenters) and their magnitude. Hypocenters are the estimated subsurface foci or centers of seismic energy release. It is not known whether these are also the locations of maximum displacement (however, it is likely). Over 90 percent of all hypocenters occur at relatively shallow depths (5 to 75 km). Approximately 80 percent of the world's epicenters occur in the mobile boundary regions between major tectonic plates where the predicted slip rates (based upon plate tectonic theory) are on the order of 5 cm/yr or more [17]. Block motion risk from natural earthquakes can be dramatically reduced by avoiding seismic regions.

Of specific significance to this investigation are the seismic zones associated with the interactions of the Western United States plate and the Alaskan-British Columbian-Washington plate which have predicted slip rates of about 5 cm/yr. The most frequent earthquake occurrences are within the Western United States in contrast to the states east of the Rocky Mountains; however, there are a number of eastern seismic

belts in which major earthquakes occasionally occur. This indicates a slower rate of in-situ stress accumulation associated with slower average plate and subplate slip rates. Nonseismic regions are termed aseismic; however, this just means that the rate of stress change is very slow. Some aseismic regions probably can be characterized by high stress where there is still risk of explosion triggering or block motions. Seismic zones should definitely be avoided, and aseismic zones will have to be evaluated for residual stress to choose sites with low explosive triggering potential.

1. REGIONAL SEISMICITY PATTERNS

Figure 2 is a map of the major seismic belts of the United States (excluding Alaska and Hawaii) [18]. Located within the aseismic regions, the nonshaded areas, are a number of candidate site areas that might be considered further for underground strategic facilities. Regional seismicity, determined by existing seismograph networks and micro-seismicity monitoring of more local regions of specific interest, is important in establishing the more stable crustal elements from those more mobile elements or seismic belts where differential slip, earthquakes, and aseismic creep predominate. The aseismic regions may contain residual stress from earlier periods of deformation so it cannot be assumed that risks of triggered block motions are eliminated by avoiding seismic regions.

2. SEISMICITY RELATED TO SURFACE FAULTING

As one proceeds from the more obvious mobile belts such as the San Andreas fault system in California to the more stable regions that might be suitable for site consideration, it is instructive to consider the distribution and magnitude of faults which have expression at the earth's surface. Some

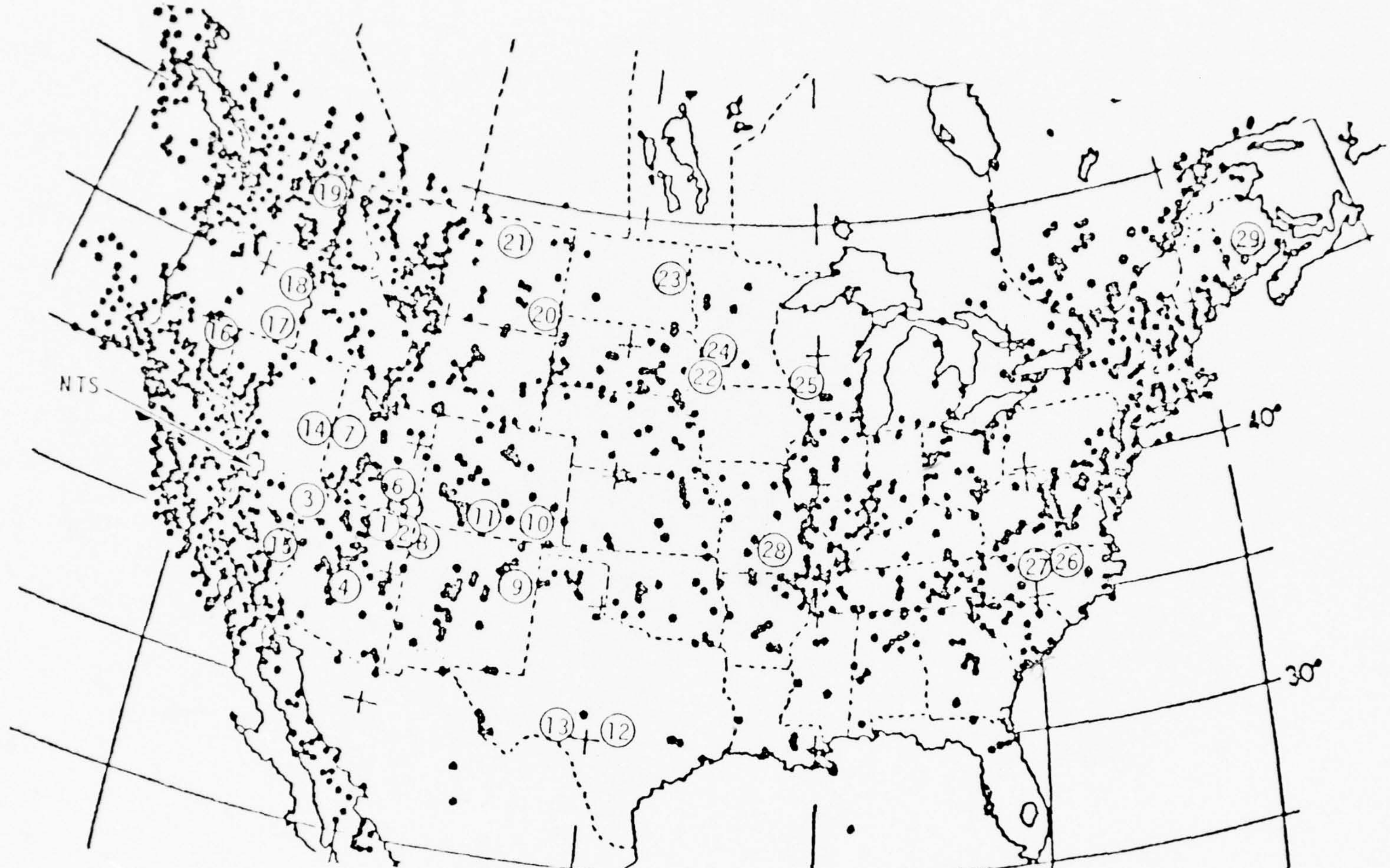

Figure 2. Preliminary Site Screening Summary Map - Showing Seismic Belts (Shaded), Historic Earthquakes (Dots), and Selected Aseismic Regions to be Considered for Locating Underground Strategic Facilities (Numbered Locations Described in Accompanying Legend)

Legend for Figure 2

Preliminary Candidate Site Areas

1. Black Mesa Basin, Ariz.
2. Defiance Uplift, Ariz.
3. Red Lake Salt, Ariz.
4. Luke Salt, Ariz.
5. Monument Uplift, Utah
6. San Rafael Swell, Utah
7. Sheeprock Uplift, Utah
8. Zuni Uplift, N. Mex.
9. Sierra Grande Arch, N. Mex.
10. Pergatoire area, Colo.
11. Rio Grande area, Colo.
12. Llano Uplift, Texas
13. Pecos Arch, Texas
14. Snake Range Uplift, Nev.
15. Needles area, Calif.
16. Modoc Lava Plateau, Calif.
17. Harley & Catlow Basins, Ore.
18. Ochoco Blue Mt. Uplift, Ore.
19. Loon Lake Bath., Wash.
20. Black Hills Uplift, Mont.
21. Sweetgrass Arch, Mont.
22. Sioux Uplift, S. Dak.
23. Eastern, S. Dakota
24. S.W. Minnesota
25. S.W. Wisconsin
26. Atlantic Coastal Plain, N.C.
27. Carolina Slate Belt, N.C.
28. Ozark Uplift, Mo.
29. N. E. Maine

will be recent, some very old and some will display movement during several periods of earth deformation. Figure 3 is a map of the major faults of the Western U.S. which also shows areas of most frequent seismic activity [19,20]. Clearly in regions where a seismic belt, or zone of seismic activity crosses existing faults, there is risk of subsequent block motion, either caused by explosion triggering or directly as a result of ongoing natural processes. Redistribution of stresses resulting from stress release in the more mobile zone can cause stress imbalances in adjacent regions where adjustment slippage might be expected to occur.

Subsurface expression of faults can be interpreted from seismic, gravity and magnetic geophysical data. These data are useful in establishing regions of possible siting interest and are especially important in areas where thick soil and recent seidments mask the local fault expressions. Areas of very low seismicity and infrequent discontinuities are preferred sites; the question of how to assess in-situ stress conditions in the aseismic regions of siting interest is discussed in Subsections 4 and 5.

3. BLOCK MOTION DISPLACEMENT AND IN-SITU STRESS

Principal aspects of the block motion problem are the uncertainty of the magnitude and spatial distribution of potential relative displacements. As yet there is little empirical or theoretical treatment of the displacement potential for faults and other discontinuities. The data that exist have not been thoroughly assembled, organized or analyzed. Clearly there is a considerable amount of scatter in the fault displacement data compared with some parameters such as earthquake magnitude; the interacting parameters affecting displacement are numerous and complex. In many instances earthquake epicenters and known faults cannot even be correlated. There is little existing basis to estimate the maximum potential

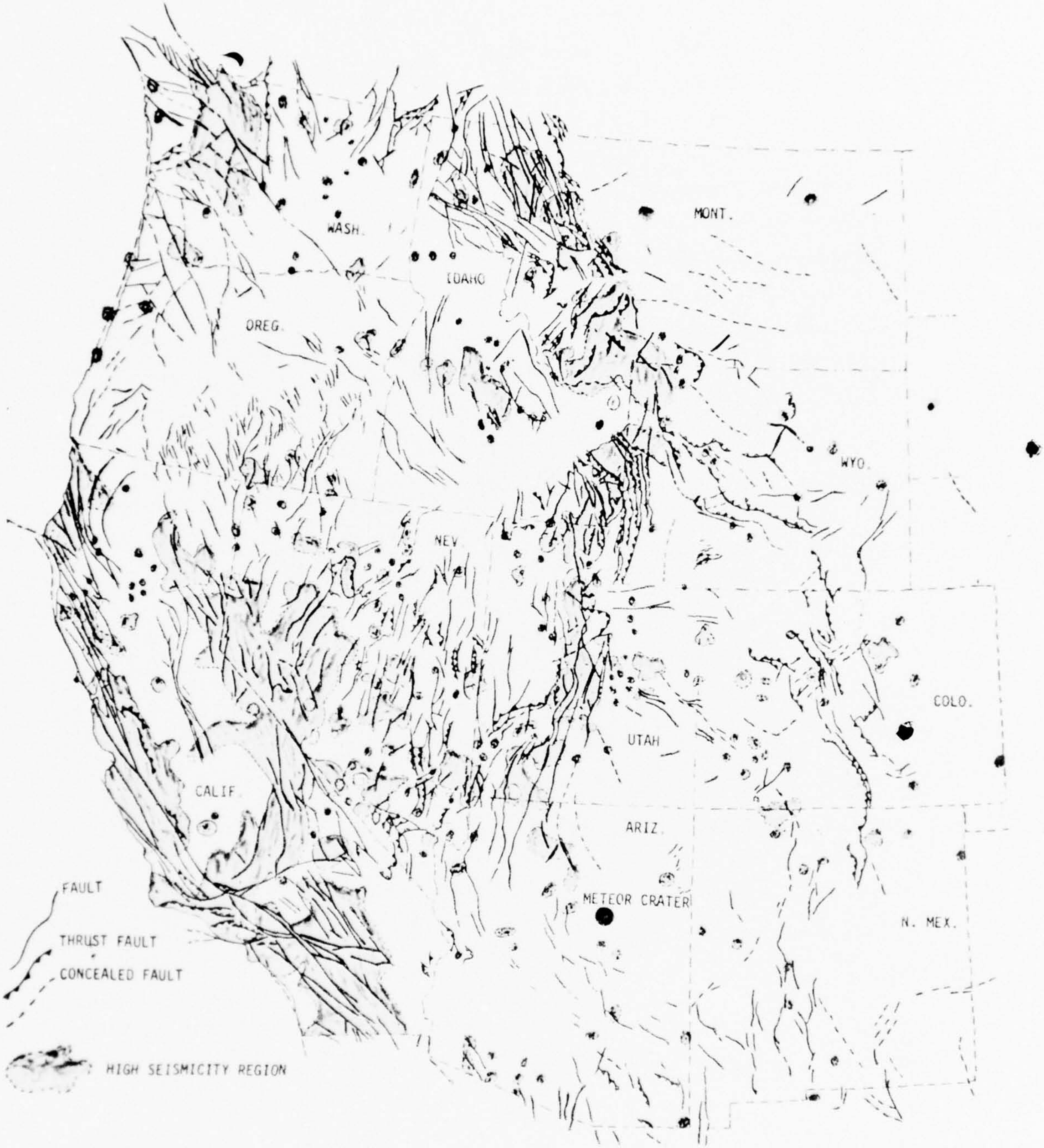

Figure 3. Major Faults and Regions of High Seismicity in the Western United States

block motion displacement of any given fault or other structural weakness because of uncertainties of in-situ stress conditions, failure criteria, and extent of the weakness or discontinuity. Improved estimates of the rigidity of crustal material, frictional properties of faults and other surfaces of slip potential, and a knowledge of both the regional in-situ stress conditions and the more local stress conditions in the vicinity of potential slip surfaces would help to quantify and reduce the block motion risk. With more information and evaluation it may be possible to assign block motion displacement potential to faults and discontinuities so that suitable sites can be found.

4. INDICATORS OF IN-SITU STRESS CONDITIONS

There are very few direct in-situ stress measurements, and increasing this data base is fundamental to an assessment of the block motion problem. Figure 4 illustrates some of the regions where in-situ stress measurements have been taken to date along with the lines of the axes of maximum lateral compressive stress. Measurement tools exist and are being improved as experience is gained. Deep-underground hydrofracturing methods appear quite satisfactory, but they are expensive. Because of the scarcity of existing in-situ stress data, it is probably better to emphasize the least-cost methods. These are near-surface measurements by overcoring or block isolation methods, and calculated in-situ stress estimates at depth obtained by analysis of seismic radiation patterns. Special attention should be given to establishing regional stress variations and their relations to block motion potential.

The direct measurement of in-situ stress is an important aspect of site evaluation and is necessary to provide data as part of a block motion research and development program. Because of the expense of these measurements and the fact that each measurement represents only a point within a region,

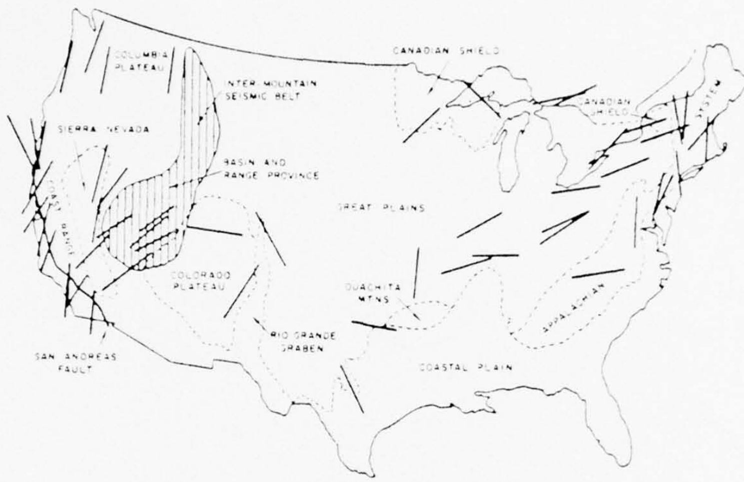

Figure 4. The Location and Orientation of Principal In-Situ Compressional Stress in the United States (Exclusive of Alaska and Hawaii [21]

it is important to develop and prove the validity of indirect methods of in-situ stress estimation. These indirect methods depend upon geologic and geophysical data and regional constraints arising from geologic arguments and implications associated with the dynamic processes pertaining to the plate tectonic theory. Of special interest to the triggered block motion problem is the need to identify areas minimal in stored tectonic stresses (imbalanced stress field) within regions that are aseismic. One approach that may prove of value as an indirect in-situ stress imbalance indicator is described in the next section.

5. POSSIBLE IN-SITU STRESS ESTIMATION USING CRUSTAL AND UPPER MANTLE PROPERTY INDICATORS

If there were lateral homogeneity of crustal and upper mantle properties, it is postulated that highly imbalanced stresses would not exist and the risk of natural or triggered block motions would be small. Even very gentle or gradual property changes might pose little concern. Making use of these assumed relations, it has been instructive to make a preliminary correlation of the steep gradient portions of selected crustal and upper mantle property variations with regional seismicity in the Western U.S. (Figure 5). The reason for making the comparison with regional seismicity is to establish that at least most of those regions of known imbalanced in-situ stress conditions are identified by the analysis. Satisfying this test might indicate that additional high gradient regions correspond with relatively imbalanced in-situ stress conditions in more aseismic regions. The properties selected for this preliminary gradient analysis and correlation with seismicity are:

1. Seismic crustal (Sc) thickness - depth to the Mohorovicic discontinuity [22].

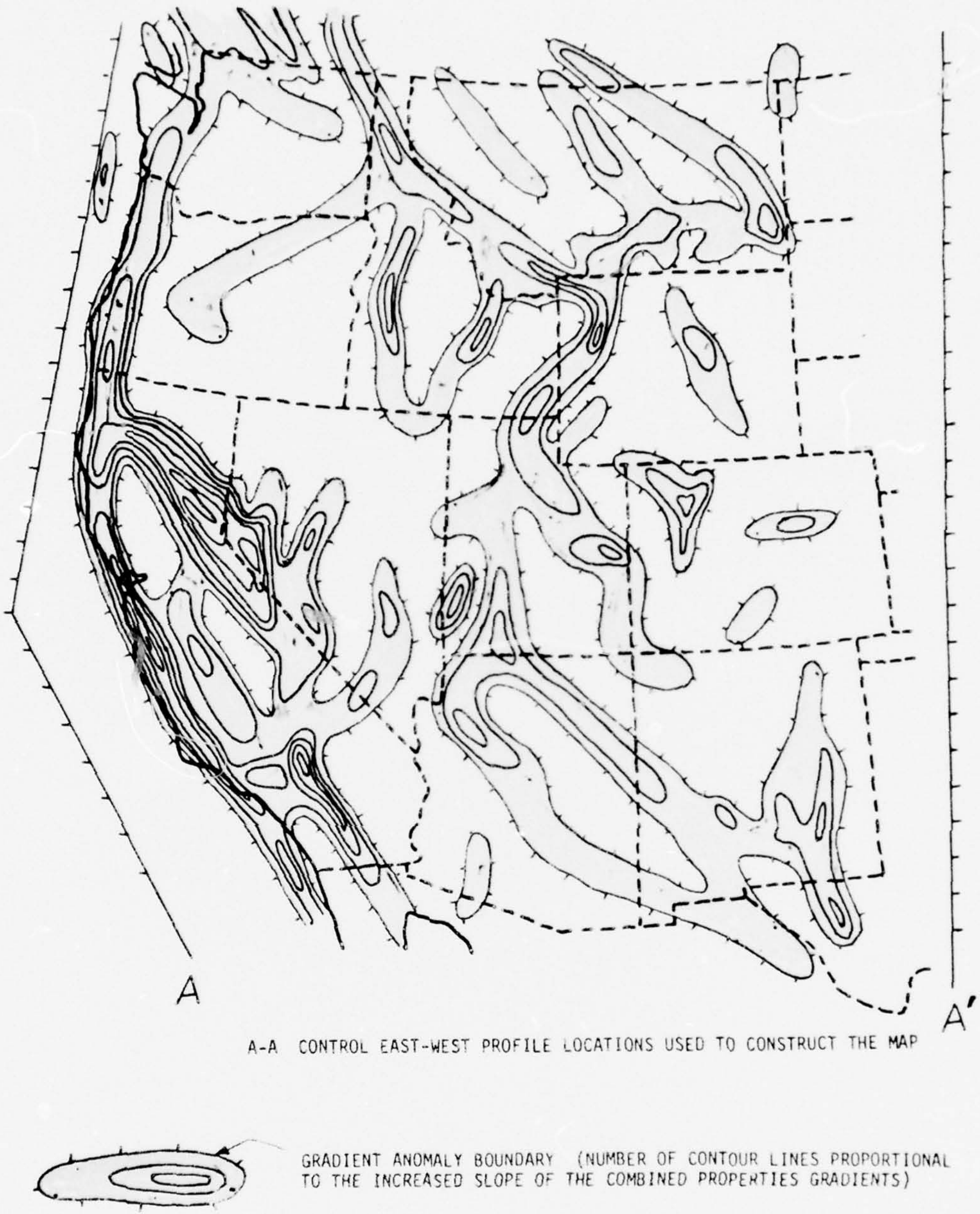

Figure 5. Composite Crustal and Upper Mantle Properties Gradient Map for the Western United States - Using Variations of the Seismic Crustal Thickness, the Magnetic Crustal Flux, and the Upper Mantle Compressional Wave Velocity

2. Magnetic crustal (Mc) thickness - depth to the Curie temperature isotherm* [23].

3. Upper mantle velocity (Pn) [24].

The seismic data (Sc and Pn) are taken from large explosion seismic crustal studies, and the magnetic data (Mc) are from the Russian Cosmos Satellite #49--in orbit from 261 to 488 km. The orbit was at a good range for determining the long (tens of kilometers) wavelength undulations of the earth's magnetic crust. The steep gradient portions of the profiles describing these properties were combined in a preliminary and rather arbitrary fashion. The original data are limited and require more accurate plotting of data locations. Also only east-west profiles were constructed. Still the regions or belts of combined steep gradient portions of the crustal and upper mantle properties match reasonably well with the major seismicity belts. In addition, other zones are indicated, such as eastern Montana and New Mexico, that may correspond to regions of possible "locked-in" or residual stress (compare Figures 2, and 3 with Figure 5).

This preliminary evaluation of major steep gradient locations of crustal and upper mantle geophysical data indicates that a more rigorous analysis may help in identifying areas of relatively imbalanced in-situ stress. This or some other approach for defining regional property variations by geophysical methods may enable construction of a matrix or map

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*Since depths to the Curie temperature isotherm have not been computed, actual magnetic flux data were used to indicate the high gradient regions. The magnetic flux data can be expected to follow gradients of the Curie temperature isotherm because the magnetometer was located at very high elevations in an orbiting satellite.

useful in site selection, screening, and ranking. Those properties that prove to reflect variations of in-situ stress can also be used to guide the locations for taking critical in-situ stress measurements in support of an R & D effort to develop a block motion predictive capability.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

There have been substantial advances in the earth sciences, specifically in the fields of rock mechanics, geodynamics, and earthquake predictions. These advances have contributed knowledge relevant to the development of an improved predictive capability for assessing the risk of explosion-induced block motion.

The major conclusion resulting from this review is that a general predictive capability to estimate displacements of faults or other weakness discontinuities resulting from large yield explosions does not exist. Presently it takes a large yield explosion test to determine if the faults or weaknesses at a site can be triggered. The empirical results of such a test are the only basis for estimating block motions to be expected from subsequent explosions. There are very few observations of unusually large subsurface block motions that indicate triggering. There are few measurements that accurately time the displacements observed at the surface that appear to have been triggered by explosions. There are no in-situ stress or failure criteria data associated with faults that are known to be susceptible to explosive triggering of block motions.

In spite of these deficiences, the potential importance of block motion phenomena to underground strategic system survivability requires that we attempt to estimate the severity of the problem and identify the means to mitigate the problem. It is in this spirit that the following additional conclusions are offered:

- Explosion-driven block motions probably extend through the crater rupture region; along near-surface spall regions; and along near-surface interfaces, joints, and faults out to several crater radii--quantitative predictions are very uncertain.

- Explosion-triggered block motions appear possible for stresses much less than 1 kbar, perhaps from strains as low as 10^{-6} cm/cm. There appears to be little or no basis for estimating magnitude of relative motions--especially at depth.
- Extrapolation of current data of observed near-surface fault motions and increased seismicity from contained nuclear explosions to block motion effects from surface/near surface explosions could exaggerate the extent of the block motion problem at depths of concern to deep based facilities.
- Site selection could reduce the potential for block motions. Preliminary reviews suggest that there are aseismic regions in the southwestern United States; however, such sites would still have "locked-in" stresses. A method for assessing regions of anomalous residual stress is needed to support site screening and selection processes.
- Quantifying the block motion problem appears difficult but not hopeless.

In addition, the following recommendations are offered:

- Applied R & D should be initiated to understand better the mechanisms behind apparent triggered block motion data from contained nuclear detonations so that more realistic estimates of the block motion threat from surface and near-surface bursts can be made.
- Applied R & D should be initiated to improve methods of anticipating adverse in-situ stress conditions in aseismic regions.
- Applied R & D should be initiated to advance the technologies of partially relieving local in-situ

stress in fracture zones and increasing the bond strength of fractures.

- Applied R & D should be initiated to identify and characterize possible candidate site regions for deep based facilities. Block motion R & D efforts could then be focused upon the needs associated with realistic site regions. Experience gained from NTS field test portions of the R & D program might then be made more transferable to non-NTS conditions associated with candidate sites.

At this time it is not known if block motion risks can be sufficiently anticipated and reduced so that underground strategic facilities can be designed and sited to survive credible threats. This review has led to the optimistic view that a reasonable R & D program can be designed and executed so that system design and siting can proceed with a high probability that the block motion problem can be reduced to acceptable levels by a combination of siting to reduce the risk and engineering to further mitigate the block motion potential.

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